Objective Estimates of Hawaiian Rainfall[1]

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THE PROBLEM of interpreting mean weather maps in terms of rainfall has been studied by numerous investigators. Klein (1949), for example, described a method applicable to the Tennessee Valley in winter. The Hawaiian rainfall problem was studied by Solot (1948 and 1950), whose methods have been of some use in estimating expected Hawaiian rainfall from the prognostic maps of the Extended Forecast Section of the U. S. Weather Bureau. While the method, in the hands of a practiced user, probably shows as much skill as the method to be described in this paper, tests (Aubert, MS.) have revealed that Solot's principles may sometimes be interpreted in quite different ways by two different forecasters, which fact points to the need for a completely objective method for making rainfall estimates. One further reason for a new study of the problem at this time is the fact that upper-level data were not readily available to Solot, and his study was based entirely on sea-level pressure patterns. An 18- to 20-year, homogeneous series of mean monthly 700-millibar charts has now been prepared by the Extended Forecast Section, and it has been deemed desirable to develop a method based on this series, since it is the 700-millibar level for which the basic prognosis is made (Namias, 1953).

The present study is a continuation of a former study (Stidd, 1954) in which the correlation field technique was explored, tested, and compared with other methods.

The main purpose of this study is to describe the development of an objective method for interpreting mean weather charts in terms of rainfall, although some attempt is made to supply physical explanations for the relationships revealed by the data.

METHOD

The correlation field technique seems well suited to the problem of relating a parameter in two dimensions (in this case, the height of the 700-mb. surface) to a point parameter (rainfall), since any linear relationships must be revealed and use is made of all data. Furthermore, since no prior knowledge of the relationships is assumed, the method is objective in its development as well as in its application.

To prepare a correlation field pattern for a given rainfall parameter, it is necessary to determine the correlation coefficients between the given rainfall and the 700-millibar heights at each of a number of grid points. These coefficients are then plotted on a base map at the respective grid points, and the pattern is analysed. Such patterns usually are found to be smooth and regular with one or two

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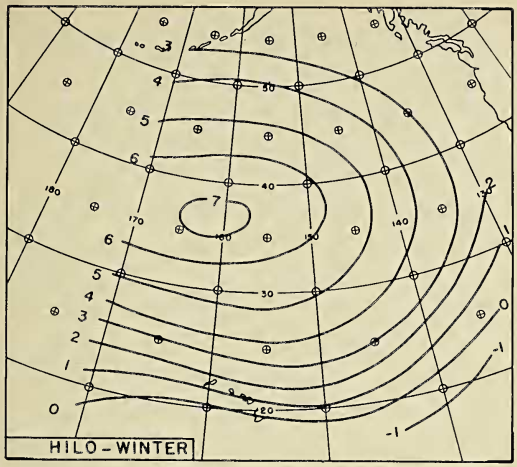

FIG. 1. Correlation field pattern of mean monthly 700-millibar height versus monthly rainfall averaged for four stations in the vicinity of Hilo. Winter months (November through April); total of 102 cases.

well-defined maxima or minima. Little, if any, smoothing is necessary in drawing isopleths to the plotted data. Although space does not allow the data to be shown on these figures, the previous paper (Stidd, 1954, fig. 6) contains the data and demonstrates how little smoothing is needed. An example is given in Figure 1. Here the rainfall parameter is the series of monthly rainfall amounts averaged for four stations in the immediate vicinity of Hilo (see map, Fig. 2). Figure 1 shows that increased pressure north of the islands favors rain at Hilo, and probably indicates that heavy rains are associated with stronger trade-wind gradients and that Hilo rainfall is very sensitive to changes in the trade-wind flow. The actual pattern of Figure 1 is suggestive of the anomalous flow pattern which is associated with heavy rainfall at Hilo. The extent to which this analogy is sound has been described in detail in the previous study (Stidd, 1954), which showed that the regression coefficients of rainfall on pressure fulfill the geostrophic equation in the same manner as the pressures themselves. Furthermore, if there were no spatial variation in the standard deviations of pressure, the correlation coefficients would, themselves, fulfill this equa-

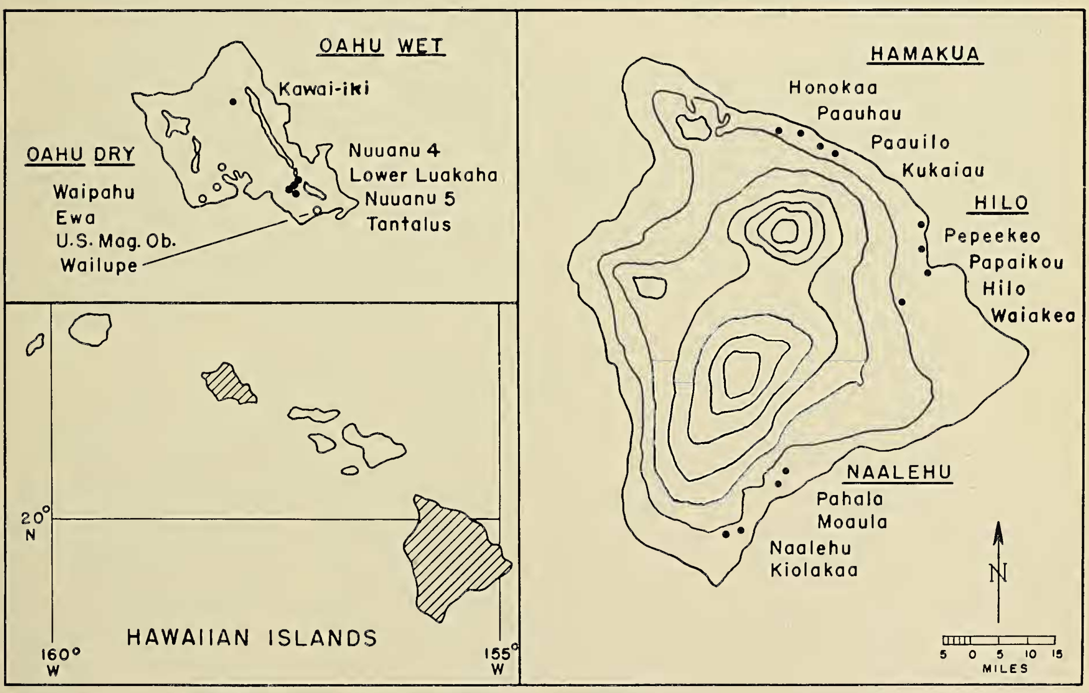

FIG. 2. Map showing location of five groups of rainfall stations in Hawaii. Terrain contours are shown at 2,000-foot intervals.

tion. Thus, it may be said that, disregarding the spatial variations in standard deviation of pressure (or, in this case, 700-mb. height), the correlation field is strictly analogous to an anomalous flow pattern. A tight gradient of the isopleths in the correlation field indicates a strong correlation of the wind tangent to those isopleths. This view of the correlation field is the basis for the discussions of the patterns.

RAINFALL PARAMETERS

Because the rainfall climate varies enormously from point to point within the Hawaiian Islands, no single rainfall parameter will be representative of conditions in general. Stidd and Leopold (1951) showed that two parameters might suffice to describe the rainfall patterns over fairly large areas.

In this study, a group of five stations from the wetter areas of Oahu have been combined to represent one of these parameters, and four dry-area stations represent the other. The combination of the two parameter estimates into an estimate for some other station is explained in the appendix.

Certain areas under the direct influence of mountains higher than 5,000 feet fail to fit into this scheme since their rainfall patterns change systematically with changes in wind direction. In the present study, several such places—Hilo, the Hamakua Coast, and Naalehu—have been tested on an individual basis.

To eliminate some of the randomness found in single-station rainfall data, each rainfall index is composed of the mean of several fairly homogeneous station values. These are listed in Table 1 and shown in Figure 2.

In order to make the rainfall indices have a more nearly normal distribution, the cube roots were taken of all the group rainfall amounts (Stidd, 1953). The assumption that the resulting sets of values are normally distributed is satisfactory in all these cases, as the stations in each group are quite homogeneous and no individual stations reported zero rainfall for any of these months. In some of the 5-day and 1-day data, which are discussed briefly in this report, zeros did occur, but not so frequently as to lead to any serious departures from normal distributions. Seasonal trends were removed by expressing the index value of a given month as a difference from the mean of all the values for that month.

The distribution of 700-millibar heights was assumed to be so nearly normal that no processing was required except for removal of the seasonal trend. This was accomplished in the same manner as for rainfall.

Five-Day Means: These were computed only for the period from November, 1946, through April, 1951. Approximately 255 pairs of values (two overlapping 5-day means per week) were available for each grid point, although, due to the fact of the overlap in 5-day periods and to the fact that serial correlations are higher in 5-day data than in monthly data,

TABLE 1

STATIONS USED IN COMPUTING RAINFALL INDICES

OAHU WET		OAHU DRY		HILO		HAMAKUA		NAALEHU	
Station	Mean annual	Station	Mean annual	Station	Mean annual	Station	Mean annual	Station	Mean annual
Kawai-iki	102.19	Ewa	20.62	Hilo	138.71	Kukaiau	105.56	Naalehu	45.24
Lower Luakaha	137.57	Wailupe	26.11	Papaikou	132.97	Pauuilo	100.81	Kiolakaa	64.46
Tantalus	100.93	Waipahu	25.07	Pepeekeo	128.57	Paauhau	67.91	Moaula Sta.	47.60
Nuuanu 4	141.77	U.S. Mag. Ob.	19.70	Waiakea M.	200.32	Honokaa	93.44	Pahala	43.37
Nuuanu 5	87.59								
Group Mean	112.01		22.90		150.14		92.18		50.17

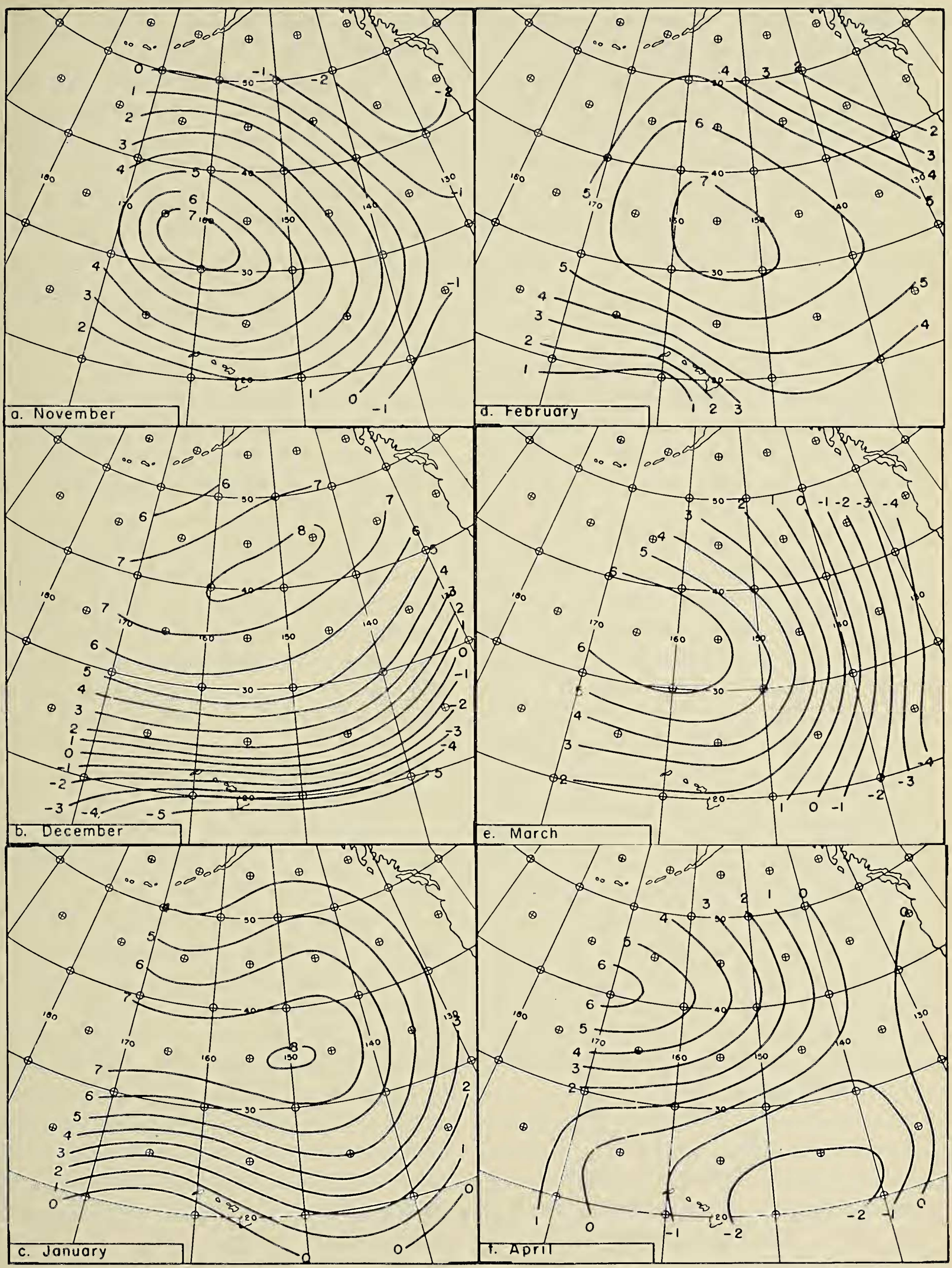

FIG. 3. Data of Figure 1 broken down to show each of the six winter months separately (17 cases in each pattern).

the samples of 5-day data would probably be equivalent to a smaller sample of independent data than would the monthly samples.

Daily Data: For comparison purposes only, daily rainfall amounts were correlated with 700-millibar heights for the months of January and February from 1946 through 1952. Only each fifth day was used, giving 77 pairs of relatively independent data at each grid point. The only rainfall index used was that for Hilo.

HILO (WINTER)

One of the strongest relationships revealed in this study was that between winter-time monthly rainfall at Hilo and the 700-millibar height at 37°N–163°W, in which a correlation of nearly +0.7 was found (Fig. 1). An objective formula based on this coefficient was found to give substantially better results on independent data (see tests) than did the estimates which were made by conventional methods. The correlation coefficient is based on 108 pairs of data, and the temptation is strong to consider it highly significant and meaningful in spite of the fact that the 108 values do not constitute a random sample and that an unknown reduction in degrees of freedom must be considered in view of the possible serial correlation in the data. Since the coefficient in question is merely the best from among many, it must be examined very critically before any significance at all can be attached to it. Chance alone, however, would not give a coefficient this high in random samples of 108 cases once in 10^9 times, and the correlation is undoubtedly significant in spite of serial correlation and its having been selected from among 32 others.

Some evidence of seasonal change in this pattern can be seen in the series of charts shown in Figure 3. Here the winter half-year pattern of Figure 1 is broken down into separate patterns for each of the months. As only 18 pairs of data go into each correlation coefficient shown in this series, the patterns would, by chance, be expected to vary from month to month; however, it is seen that in each case the correlation is quite high at 37°N–163°W.

A physical explanation for the position of this key point is not difficult to provide on the basis of orography, and, as orographic rainfall is of predominant importance to Hilo, this explanation is likely to suffice. The mountains behind Hilo enclose it in an arc which curves gently through approximately 60 degrees. Thus, trade winds ranging in direction from due east to NNE will be captured and lifted rather than deflected around the mountain mass (see map, Fig. 2). It may be supposed, then, that Hilo rainfall will be quite responsive to the strength of the trade winds and that, providing the winds are trades, the precise direction is not particularly important.

In Figure 1 the direction and gradient of the isopleths over Hilo confirm this strong relationship between trade winds and rainfall. The maximum correlation at 37°N–163°W simply indicates the spot where pressure anomalies are most closely related to flow anomalies in the Hilo area. If low latitude data were available, it might be possible to find a center of high negative correlation to the SSW of Hilo.

Since the "strength of the trade winds" is proposed as the physical mechanism between the pressure at 37°N–163°W and rainfall at Hilo, it might be supposed that a more nearly direct measure of trade-wind strength would have a still higher correlation. It is possible to test the gradient directly by correlating the difference in height between two grid points with Hilo rainfall. Such a correlation using the grid points 25°N–145°W and 20°N–140°W gave a coefficient of only 0.38. The discrepancy between the strength of this "direct" correlation and the best coefficient from the correlation field is not easy to understand. It emphasizes once again the difficulty of intuitive selection of parameters, particularly when mean charts and long-range problems are involved.

Figure 4*a* shows a correlation field which associates 5-day mean 700-millibar heights with 5-day rainfall totals at Hilo. It is different from the monthly chart of Figure 1 in three noteworthy respects:

1. The maximum correlation coefficient is much lower.
2. A negative correlation is found in the Hawaiian area.
3. The positive maximum is displaced well to the east of its monthly position.

This chart points up the need for considering the short-period phenomena which go to make up the mean monthly pressure maps and indicates that the reasoning, previously presented to explain the monthly pattern, is not completely adequate. Further evidence for this is provided by Figure 4*b*, which shows the correlation field relating 24-hour rainfall amounts at Hilo to mid-period 700-millibar heights. This chart substantiates Figure 4*a* in showing a negative correlation near Hawaii, but the positive maximum is displaced back to the approximate position which it occupies on the monthly chart. In considering these two shorter-period charts, it should be borne in mind that they include only 5 or 7 years of data and that, in addition, the 24-hour-amounts chart is only for the months of January and February, so that the apparent differences may be due in part to the peculiarities of the particular time periods which the charts represent. The author suspects that this consideration might account for the zonal shift in the positive center but is inadequate to explain the negative correlation in the island area.

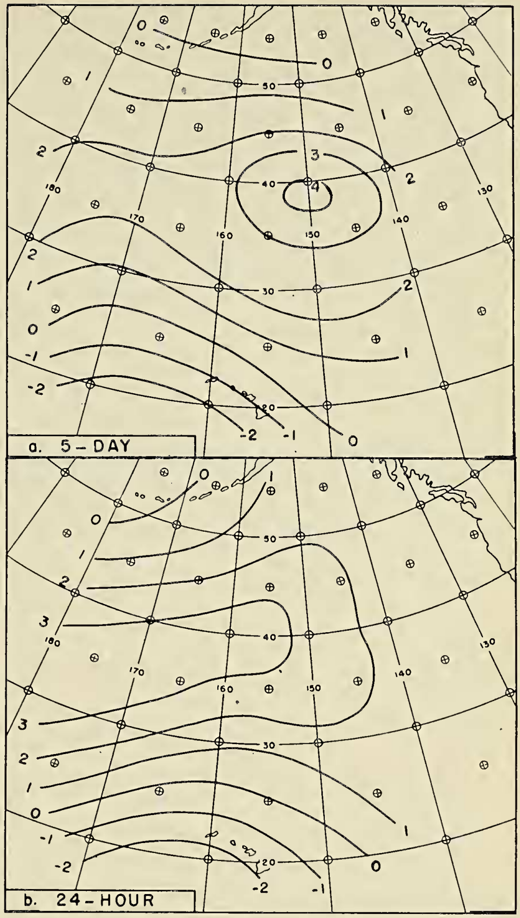

FIG. 4. Correlation field patterns of 700-millibar height versus Hilo area rainfall. *a*, Five-day means, November–April, 255 cases; *b*, twenty-four-hour rainfall amounts and mid-period synoptic 700-millibar heights, data taken every fifth day from the months of January and February, 66 cases.

The smaller correlation coefficients displayed by the shorter periods are due in part to the larger degree of randomness or "noise" in the basic data. This is largely suppressed in the process of taking 30-day means. In the previous study (Stidd, 1954), short-period data for the Tennessee Valley gave patterns similar to the monthly data, although the strengths of the relationships were reduced in about the same degree as that shown here. The Hawaiian short-period patterns, however, are distinctly "different" from the monthly patterns.

It is evident that patterns associated with daily rainfall amounts need not be the same as those for monthly amounts. Suppose that a strong positive relationship exists between pressure at a given point and concurrent rainfall at some other point. During periods when no rain is falling, the pressure at the given point will be low, and in a month's time it might happen that nearly all the days are free of rainfall and marked by low pressure at the

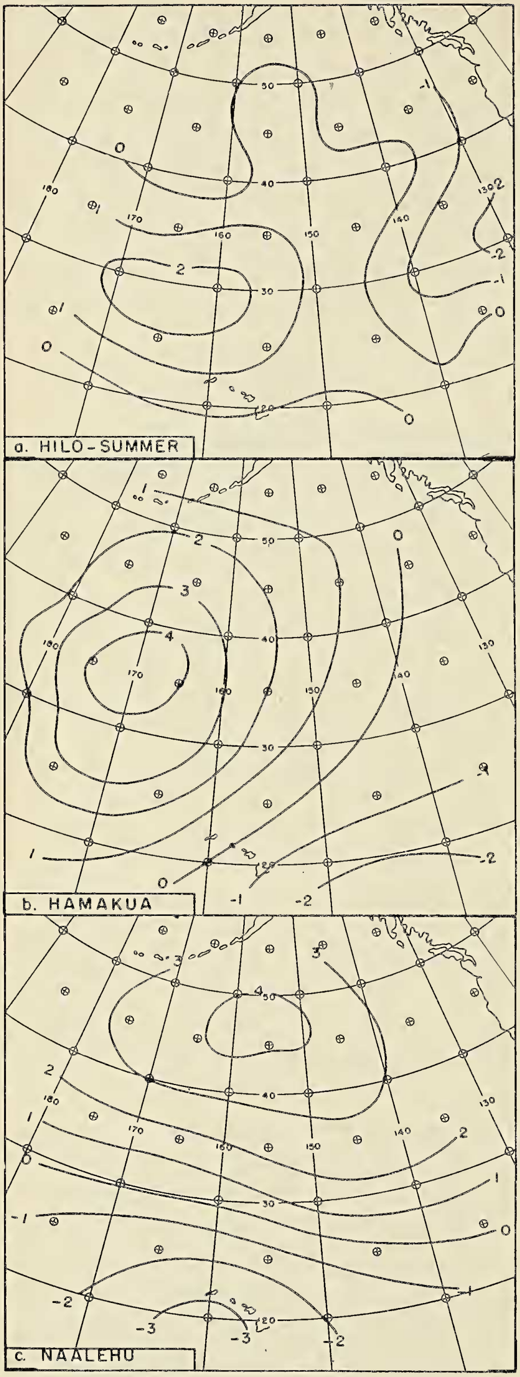

FIG. 5. Correlation field patterns of mean monthly 700-millibar height versus monthly rainfall amounts. *a*, Hilo area, August, 17 cases; *b*, Hamakua Coast, winter months, 102 cases; *c*, Naalehu area, winter months, 102 cases.

given point. In one day's time, however, it is possible for enough rain to fall to yield an above-normal total for the entire month. The high pressure, associated with this one day's rain, would not compensate for the many days of low pressure associated with the drought, and the strong daily relationship would break down on a monthly mean basis. In other words, the problem stems from the fact that there are no "negative amounts" of rainfall to compensate for the few cases of exceptionally heavy rainfall.

Thus, on a mean monthly map the point of maximum correlation may be shifted from the place where it appears on a daily map. The new position may be one at which high pressure favors persistent or repeated periods of rainfall but not, necessarily, concurrent rainfall.

HILO (SUMMER)

Figure 5*a* shows the correlation field of August 700-millibar heights versus Hilo rainfall. The highest correlation on this chart is no more than one would expect to find by chance alone, and it is evident that Hilo summer rainfall has little, if any, linear dependency on the mean monthly 700-millibar chart. This is probably due to the fact that trade winds over Hilo in summer are so deep and steady that their strength cannot be a critical factor and the fluctuations in rainfall must be associated with something other than the fluctuations in trade-wind strength.

This very weak summer relationship is characteristic of all the rainfall indices tested, and thus far no alternative approach to the summer problem has led to very satisfactory long-period objective estimates. These low correlations indicate that Solot's method is likewise inadequate in the summer months.

HAMAKUA

In contrast to the strong relationship shown by the Hilo winter correlation field (Fig. 1) is the much weaker relationship for the Hamakua index (Fig. 5*b*). This rainfall index is based on the records from a group of gauges spaced along the coast at distances of 27 to 37 miles from Hilo. The slopes behind these stations are convex to the trades, making the precise direction of the trades a more important factor than it is at Hilo. The convexity also has the effect of giving each station a slightly different exposure, with consequent loss in homogeneity.

Smaller mean annual rainfall amounts in this area and greater inhomogeneity among stations suggest that there is more randomness in the Hamakua index than in the Hilo index, and this randomness helps reduce the relationship of the index to the 700-millibar-height field. Comparison of Figure 5*b* with Figure 1 shows that the relationship is reduced to a marked degree, the highest correlation coefficient between Hamakua rainfall and 700-millibar heights being only 0.44.

NAALEHU

Figure 5*c* shows the winter monthly pattern for the Naalehu index. This is a much drier area, responding more to cyclonic activity and less to trade winds than does Hilo. It will be seen to be very similar to the pattern for dry areas on the Island of Oahu, a fact which helps establish the principle that stations having equal mean annual rainfalls respond alike to a given rainfall stimulus.

The high positive center on this pattern is far to the north, presumably the more readily to allow the development of negative values in the immediate vicinity of the Islands. It is unfortunate that data from more southerly latitudes are not available. Experience with patterns of this sort in other areas indicates that the nearby negative center might well be greater in magnitude than the distant positive center. In fact, it is evident in all the patterns that important information could be found in the area south of the Islands.

WET INDEX

Figure 6*a* shows the correlation field pattern associated with the monthly rainfall from

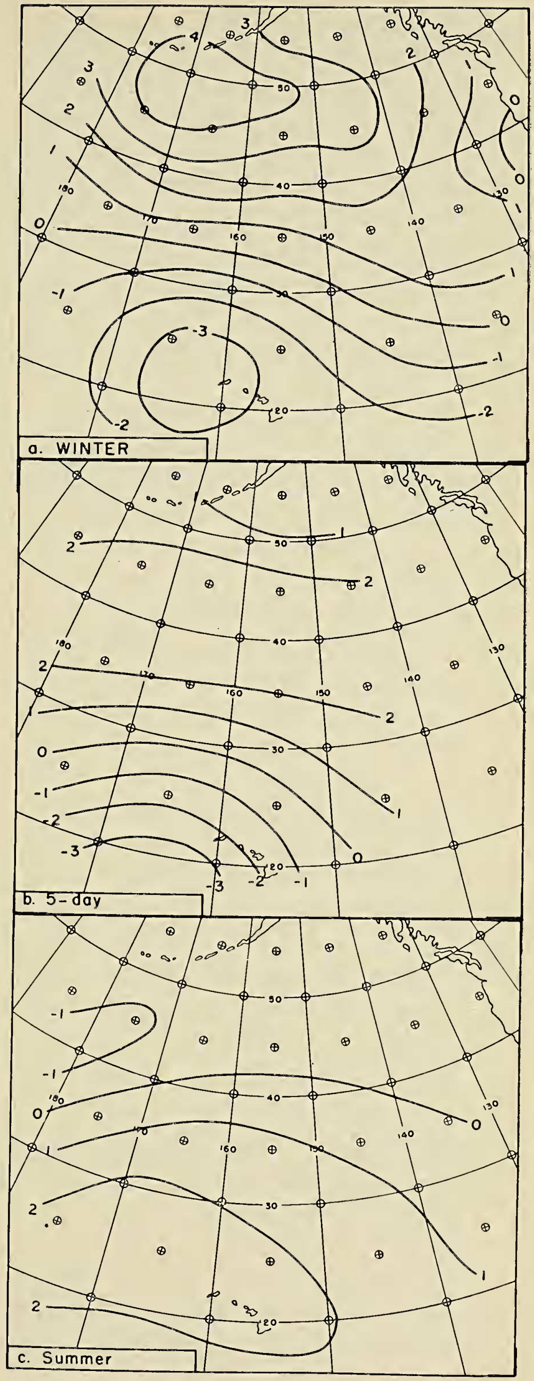

FIG. 6. Correlation field patterns of 700-millibar height versus Oahu wet-index (average of five high-rainfall stations on Island of Oahu). *a*, Monthly amounts, winter, 102 cases; *b*, five-day amounts, winter, 255 cases; *c*, monthly amounts, summer (May through October), 102 cases.

a group of five stations from the wet areas of Oahu. The group mean annual rainfall of 112 inches indicates that these stations derive the bulk of their rainfall from orographic effects, and, as might be expected, the pattern of Figure *6a* is somewhat similar to that for the Hilo area (Fig. 1). There are three important differences, however, as follows:

1. The positive center is shifted 5 degrees northward.

2. The correlation is negative in the island area.

3. The over-all strength of the relationship is not as great as in the case for Hilo.

The northward shift and negative correlation may indicate a somewhat greater importance of cyclonic activity to the monthly rainfall totals of these wet Oahu stations. The fact that the over-all relationship seems weaker would indicate, as in the case of the Hamakua stations, that rainfall of the wet Oahu stations is not as greatly dependent on the strength of the trade winds as is that of Hilo.

Five-day rainfall amounts for these wet Oahu stations are shown by Figure *6b* to be more dependent on cyclonic activity and less dependent on the strength of the trades. This is indicated by a negative correlation probably greater than —0.30 just to the southwest of the Islands, a stronger southerly gradient of flow over the Islands, and a much weaker positive belt to the north.

As with Hilo rainfall, summer data fail to reveal any useful relationship between the wet index and the 700-millibar surface. Figure *6c* shows the pattern for the season May through October.

DRY INDEX

In contrast to the wet-index pattern of Figure *6a*, Figure *7a* shows the pattern for a group of four stations chosen from the dry areas of the Island of Oahu. In this pattern the cyclonic origin of the rainfall is emphasized and the similarity of this pattern to that for Naalehu (Fig. *5c*) is marked. The pattern of Figure *7b*, 5-day rainfall amounts for the dry-index stations, indicates that the short-period amounts are almost purely dependent on cyclonic activity. The correlation coefficient −0.52 is larger than is usually found with 5-day data.

OBJECTIVE ESTIMATES

In practice it has been found difficult to obtain high multiple correlation coefficients by the combination of several selected points from the 700-millibar chart. In the case of Hilo, for instance, the relationship between the 700-millibar surface and rainfall cannot be boosted, by any significant amount, above the 0.69 expressed by the best simple correlation coefficient in Figure 1. In most other cases, where reasonably high negative correlations are found in addition to the positive center, a combination of two points—those showing greatest positive and greatest negative simple correlation—gives a multiple correlation that is difficult to improve upon by the addition of other points.

Multiple regression equations were developed, by means of which the dry index and the wet index could each be estimated from a knowledge of the heights of two points on the 700-millibar surface. Given the wet and dry indices, rainfall amounts for various stations can be estimated from a knowledge of their mean annual rainfalls. The method has been used in forecasting by applying the regression equations to data from the prognostic monthly mean charts. During the past 2 years, 24 estimates made by the objective method alone had a slightly higher average skill score than the final predictions, which frequently were modifications of the objective estimates.

For those who may wish to apply the method, the regression equations and other essential information are given in an appendix.

COMPARISON TEST

It was mentioned in the introduction that a test had been made on the ability of forecasters to interpret mean charts in terms of

Hawaiian rainfall. This test (Aubert, MS.) covered the period February, 1948, through January, 1950. An experienced long-range forecaster and a meteorologist without much long-range experience worked independently, using observed mean monthly sea-level maps to estimate the rainfall for various Hawaiian stations. They relied heavily on Solot's findings. In order to compare the present method of objective estimates with this test, the 2-year period involved in the test was deleted from the data of the present study, and all the necessary correlations were recomputed. New key points were chosen and the regression constants were altered so that the resulting regression equations were entirely independent of any of the data from the test period.

In that portion of the original test which dealt with winter months, the experienced forecaster had a skill score of 0.25 as against a score of 0.20 for the inexperienced forecaster. The objective method, computed by a statistical clerk, had a skill score of 0.29.

These scores may be interpreted in the usual sense, namely, that they are the correct portion of the group of forecasts which would have been in error had no skill been involved. Without more detailed information they have little meaning in the absolute sense, but they are stated here to indicate relative abilities. Thus, all tests to date seem to indicate that objective methods based on correlation field patterns can do at least as well as the subjective methods of trained forecasters.

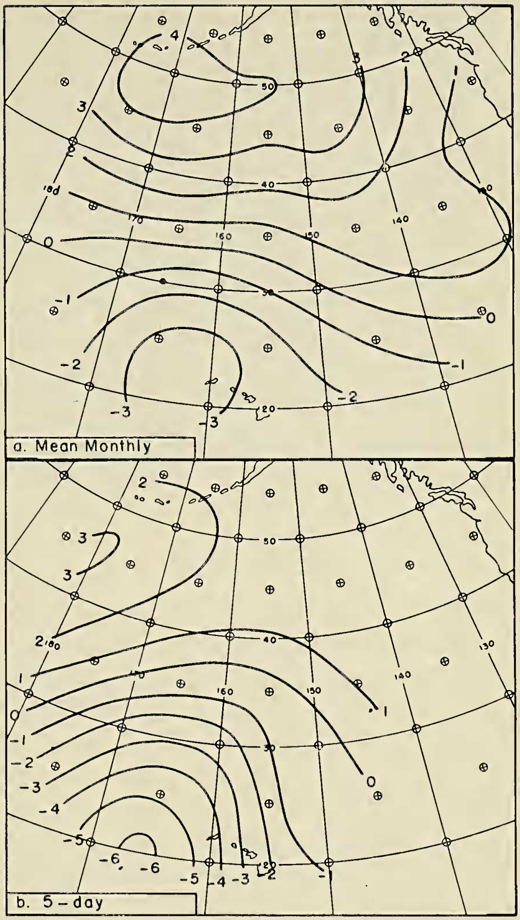

FIG. 7. Correlation field patterns of 700-millibar height versus Oahu dry-index (average of four low-rainfall stations on Island of Oahu). *a*, Monthly amounts, winter, 102 cases; *b*, five-day amounts, winter, 255 cases.

LIMITATIONS OF METHOD

The chief objection to the correlation field method is the fact that only one or two points on the map are considered and all the rest of the map is completely disregarded. As has previously been stated, it does not seem feasible to overcome this objection simply by the addition of more points, because each added point boosts the multiple correlation only very slightly. An alternative approach to the problem would be to attempt to express all the salient features of the map in a few simple terms, using the method of orthogonal polynomials as described by Wadsworth (1948) or the method of spherical harmonics as described by Haurwitz and Craig (1952). This relatively small number of parameters could then be correlated with rainfall and the best ones chosen as predictors. Such an approach tested on data from the United States mainland, showed little improvement over the correlation field method where the key-point correlations were ±0.6 or higher. Where the correlation fields were weaker than this, however, improvement was indicated.

With regard to the use of only two points, practice seems to indicate that they may be adequate as estimators from an *observed* map but inadequate when used with prognostic charts. This is due to the fact that a prognostic chart may show considerable skill in anticipating the large-scale features of the observed map a month later and yet be in error at the key point or points on which the rainfall forecast is based. Skill scores for Hilo, for instance, have been significantly lower than those for stations on the Islands farther north, and yet the correlation field shows a stronger relationship of the observed 700-millibar chart to Hilo than to any other station.

CONCLUSIONS

Objective long-range estimates of Hawaiian rainfall from observed 700-millibar patterns can be made with a general accuracy at least equal to that attained by a forecaster using conventional methods. The correlation fields shed some light on the mechanisms of mean monthly rainfall processes in Hawaii and suggest limits to our ability to make rainfall estimates from a knowledge of the 700-millibar field.

The use of key points as described in this study comprises a forecast system which is very sensitive to errors on the prognostic charts. It may be possible to overcome this difficulty by the use of orthogonal methods of map description.

Substantial improvement in monthly rainfall forecast accuracy will depend in part on improvement of the prognostic 700-millibar charts and in part on the discovery of rainfall-related factors other than those found in the mean pressure field.

APPENDIX

Regression equations for estimating Hawaiian monthly rainfall amounts from prognostic mean monthly 700-millibar charts. (Height differences are expressed in tens of feet.)

(1) $W = 0.034A - 0.01B$

where W = Oahu—Wet

A = difference from normal 700-mb. height at 42°N–163°W

B = difference from normal 700-mb. height at 20°N–160°W

(2) $D = 0.02C - 0.04E$

where D = Oahu—Dry

C = difference from normal 700-mb. height at 49°N–163°W

E = difference from normal 700-mb. height at 22°N–163°W

When the Oahu-wet and Oahu-dry indices have been computed, an individual station can be estimated as follows:

(3) $$t_s = D + \frac{\bar{R}a - 23}{89}(W - D)$$

where t_s = the expected standard departure from normal (units of one standard deviation) of the rainfall for a given station, and

$\bar{R}a$ = the mean annual rainfall of the station.

The constants 23 and 89 are, respectively, the rounded mean annual dry-index and wet-index-dry-index differences as determined from Table 1.

Some stations, such as Hilo, which may not fit into the wet- and dry-index system of classification should not be estimated by means of formula 3. The formula used for Hilo is (4) $t_H = 0.04F$

where t_H = the expected standard departure from normal of Hilo rainfall, and

F = the difference from normal 700-mb. height at 37°N – 163°W.

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